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Integrated solution in an office room with diffuse ceiling ventilation and thermally activated building constructions

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Abstract

An integrated system is proposed in this study to combine diffuse ceiling ventilation with a thermally activated building construction (TABS), aiming to provide cooling/ heating and ventilation to an office room all year around. The performance of the integrated system is evaluated by full-scale experiments in a climate chamber. The experimental results indicate that diffuse ceiling can significantly improve thermal comfort in the occupied zone, by reducing draught risk and vertical temperature gradient. The linear function between pressure drop and air change rate points out that the air flow through diffuse ceiling is laminar. A thermal decay is found in the plenum air and the thermal performance of TABS may be influenced by water flow and air flow direction.

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Keywords: Diffuse ceiling ventilation; Thermally activated building constructions; Thermal comfort; Experimental study

1. Introduction

A novel ventilation concept named as diffuse ceiling ventilation was proposed recently, where the space above a suspended ceiling is used as a plenum and fresh air is supplied to the occupied zone through perforations in the acoustic ceiling panels. Different from conventional ventilation systems that outdoor air needs to be preheated during winter, the cool outdoor air can be directly supplied into the room without significant draught risk by using

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diffuse ceiling ventilation [1][2]. Another advantage of this ventilation system is its low pressure drop compared with conventional duct system, making it possible to implement with natural ventilation [3][4][5]. These characteristics make diffuse ceiling ventilation especially suitable for office room with high internal heat load and high ventilation demand. However, in summer or extremely winter, ventilation is often insufficient to guarantee a comfortable thermal environment. Then, thermally activated building system (TABS) could serve as a supplementary cooling or heating system. TABS extracts or supplies heat from or to a room by radiation and convection heat exchange between the cooled or heated concrete slab and the rest of room. And due to the large heat transfer surface, it is possible to cool or heat with high efficiency, even with slight temperature difference between slab surface and indoor temperature [6].

Although, the two individual technologies (TABS and diffuse ceiling ventilation) have been proved by extensive researches and implemented in number of existing projects, the performance of the integrated system is still unidentified. Diffuse ceiling ventilation requires most or even entire ceiling surface to be covered by suspended ceiling. While, the design principle of TABS is to ensure that large slab surface exposes to the room. Therefore, the combination will obviously influence the effectiveness of TABS and diffuse ceiling ventilation.

The objective of this paper is to analyze the performance of an integrated system with diffuse ceiling ventilation and TABS in an office room. A full scale experiment is carried out in a climate chamber with typical office layout. The thermal comfort in the occupied zone is compared between the cases without diffuse ceiling and with diffuse ceiling, in terms of draft risk, vertical air temperature distribution and radiant asymmetry. The thermal process and air flow pattern in the plenum are also investigated.

2. Experimental description

The measurements are carried out in climate chambers located in Aalborg University, and the dimensions of chambers are illustrated in Figure 1. The cold chamber simulates outdoor environment and the hot chamber simulates a two-floor office building. The hot chamber is divided into three zones. The lower zone represents an office where the thermal comfort is mainly investigated, also named as test room. And upper zone represents a second floor office which used to investigate the thermal behavior of TABS. Both upper zone and lower zone are enclosed by a surrounding zone, used to eliminate heat loss or heat gain from the lab.

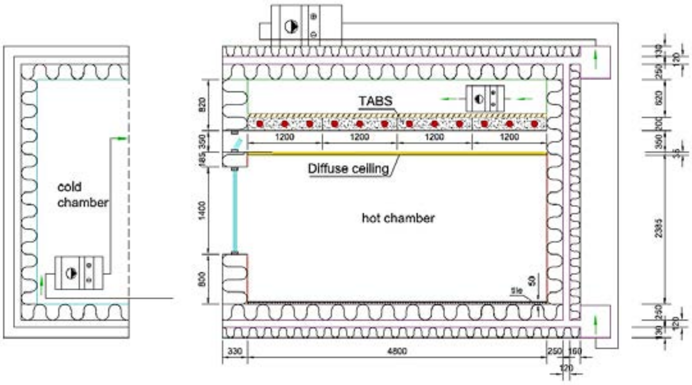


Fig.1 . Climate chambers: Lateral view

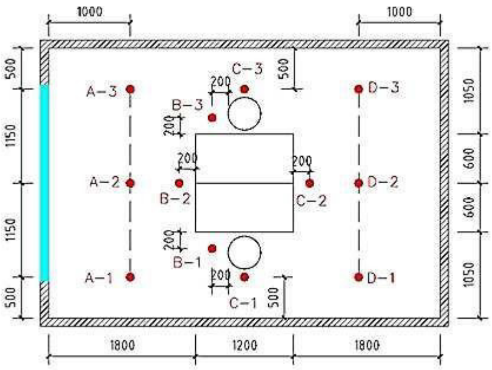


Fig. 2. Layout of test room

There are four pieces of concrete slabs composed the thermally activated ceiling, which separate the lower zone and the upper zone. The water carrying pipes with a diameter of 20 mm are embedded in the hollow core concrete slab. The pipes are placed 5 mm above the slab lower surface to ensure most of heat could transfer to the test room, and the pipes are connected in series between slabs. The diffuse ceiling is mounted below concrete slab with a distance of 350 mm and covers the entire ceiling area. The diffuse ceiling is made by cement-bonded wood wool panels which are permeable to air.

The cold chamber and hot chamber are separated by a façade. There are six windows located on the façade, upper three are served as inlet facing to the plenum and lower three are closed during entire measurement period. The exhaust is placed on the left corner of the façade just above the floor. Air is drawn from the test room into the cold chamber through an exhaust fan, cooled or heated by air handling unit and supplied to the test room. The effective heat transfer coefficient of the façade is measured to be 0.61 W/m2.K based on ISO 8990 method [7].

The test room is set up as a two-person office room, which consists of two manikins, two computers, two monitors, two tables, two chairs and two desk lamps in a symmetrically placement in the occupied zone, as seen in Figure 2. The total heat load is 450.5 W, corresponding to 28.4 W/m2.

The measurements are carried out for 6 cases with different supply air temperature, TABS activation modes and with/ without diffuse ceiling, and the detail is presented in Table 1. A constant air change rate of 2 h^{-1} and heat load of 450.5 W are used in the all measurements. The measurements are conducted under steady state condition. Depending on the set up temperature and the condition of previous measurements, especially without or with diffuse ceiling, it could take 3-5 days to reach steady states and data collection of steady states takes approximately 1 day.

Table 1. Boundary conditions for different cases.

Case	Air change rate (h^{-1})	Supply air temperature (°C)	Heat load (W)	TABS water supply temperature (°C)	TABS flow rate (m^3/h)	Diffuse ceiling
1	2	-7.1	450.5	36.38	134.5	-
2	2	9.21	450.5	-	-	-
3	2	23.82	450.5	17.29	140	-
4	2	-6.87	450.5	30.89	136	Y
5	2	9.46	450.5	-	-	Y
6	2	24.1	450.5	8.1	209	Y

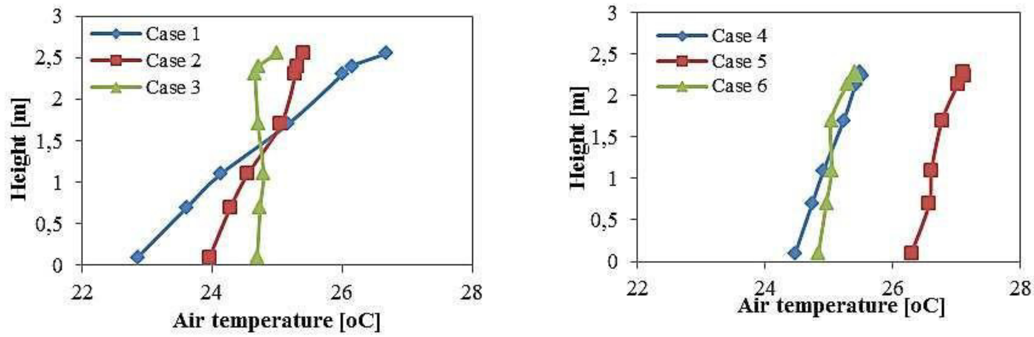
The measurements mainly focus on thermal comfort in the test room and thermal process and air flow pattern in the plenum. In total, there are 115 K types thermocouples used to monitor temperatures, including ventilation supply and return temperature, vertical temperature profiles in the occupied zone, air temperature in the plenum, internal surface temperature, upper and lower surface temperature of concrete slabs, TABS supply and return water temperature, upper and lower surface temperature of diffuse ceiling.

Air velocity is measured by hot sphere anemometer. There are 19 anemometers in total to measure air velocity in the occupied zone and in the plenum. The pressure drop across the diffuse ceiling is measurement by FCO510 micromanometer by locating pressure sensors in the plenum and test room. The pressure drop is measured under different air flow rates.

3. Experimental results and discussion

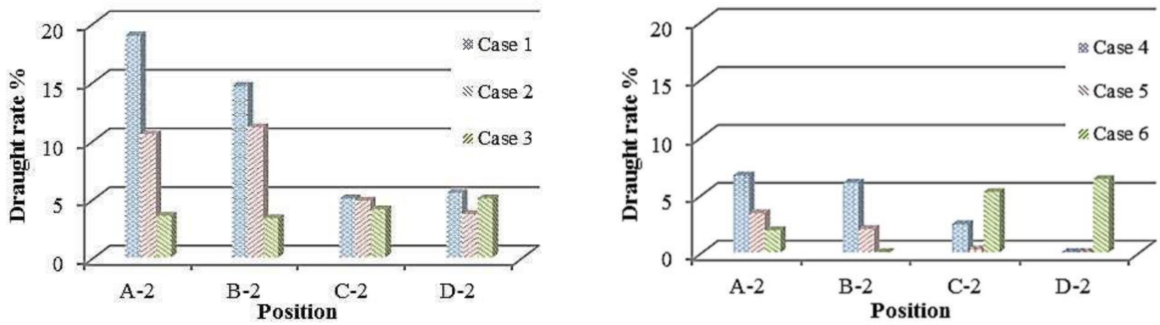
3.1. Thermal comfort

Vertical air temperature difference is an important parameter on evaluating local thermal comfort. Occupants will feel discomfort when there is a high temperature difference between head and ankles. The vertical temperature profiles are measured at 7 different height (without diffuse ceiling: 0.1 m, 0.6 m, 1.1 m, 1.7 m, 2.3 m, 2.4 m, 2.55 m; with diffuse ceiling: 0.1 m, 0.6 m, 1.1 m, 1.7 m, 2.135 m, 2.235 m and 2.285 m). As presented in Figure 3, the highest vertical temperature gradient is found in the case with heated ceiling and without diffuse ceiling (Case 1), where the vertical temperature gradient reaches 1.5 °C/m and the temperature difference between head and ankle is 1.3 °C for sitting person and 2.31 °C for standing person. With the same boundary condition, the temperature gradient in the room with diffuse ceiling (Case 4) is only 0.44 °C/m. This indicates the air in the room mix well with the help of diffuse ceiling. In addition, the supply air temperature has strong influence on the vertical temperature gradient in the cases without diffuse ceiling, but this effect is eliminated by using diffuse ceiling ventilation.



(a) (b)

Fig. 3. Vertical air temperature gradient (a) Cases without diffuse ceiling (b) Case with diffuse ceiling



(a) (b)

Fig. 4. Draught rate distribution measured at different horizontal positions (a) Cases without diffuse ceiling (b) Cases with diffuse ceiling

Draught is one of the most common causes of complaint in ventilated buildings. Draught rates (DR) are analyzed at 4 positions along the length of the room and at 3 heights 0.1 m, 1.1 m and 1.7 m. Based on the measurement results, the highest DR is observed at 0.1 m in all cases, therefore, only the DR at ankle level is discussed here and shown in Figure 4. A cold downdraught is found at the position closed to the façade in the room without diffuse ceiling when the supply air is -7 ºC (Case 1), where the DR reaches 18.9% and is closed to the comfort limitation of 20% in Category B[8]. The high draught risk is because the cold air drops in a short distance from inlet due to gravity forming a downward flow and the cold façade surface exacerbates the situation. However, the draught risk significantly reduces by using diffuse ceiling. Diffuse ceiling forms a pressured chamber, allowing the air distributed through the entire ceiling area and prevent the downward flow closed to inlet. On the other hand, while the supply air temperature increases, the draught rate reduces in both conditions (with or without diffuse ceiling) and high DR moves from place closed to façade to the deeper part of the room.

Differences in room enclosure temperature can lead to thermal discomfort due to radiant asymmetry. Table 2 illustrates the asymmetric radiation from a cool or warm ceiling and the percentage dissatisfied (PD). When occupants directly expose to the wall TABS surface, high discomfort is presented and PD exceeds the limitation of 5% in Category B [8], while no discomfort is observed when TABS is activated as cooled ceiling. This is due to the fact that people are more sensitive to warm ceiling than the cool one. However, no discomfort due to radiant temperature asymmetry is found after utilization of diffuse ceiling ventilation. Because TABS is encapsulated by diffuse ceiling and the radiation effect is reduced simultaneously.

Table 2. Radiant temperature asymmetry

Case	1	2	3	4	5	6
$T_{TABS, low}$ [ºC]	32,1	24,9	20,6	27,3	20,1	10,8
$T_{diff, low}$ [ºC]	-	-	-	23,4	24,8	22,7
Δt_{pr} [ºC]	4,5	0,3	1,5	0,6	0,7	0,9
PD %	5,86	0,01	0,01	0,01	0,01	0,01

3.2. Thermal process and air flow pattern in the plenum

The use of plenum to deliver air into the occupied zone is one of the key features that distinguish diffuse ceiling ventilation from the conventional ducted air distribution system. Low pressure drop is required in this system, making it is possible to run with nature ventilation. Figure 5 presents the pressure drop across the single acoustic ceiling tile and those across the entire ceiling area under different air cha*nge* rate conditions. From the linear increase of pressure drop with air change rate, it can be concluded that the flow through diffuse ceiling is laminar.

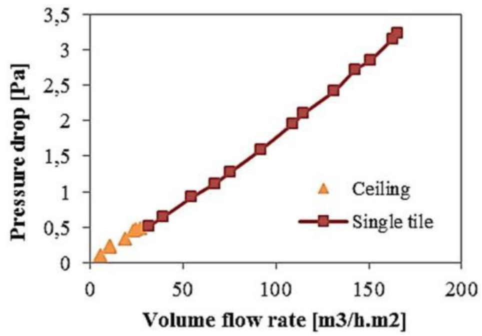
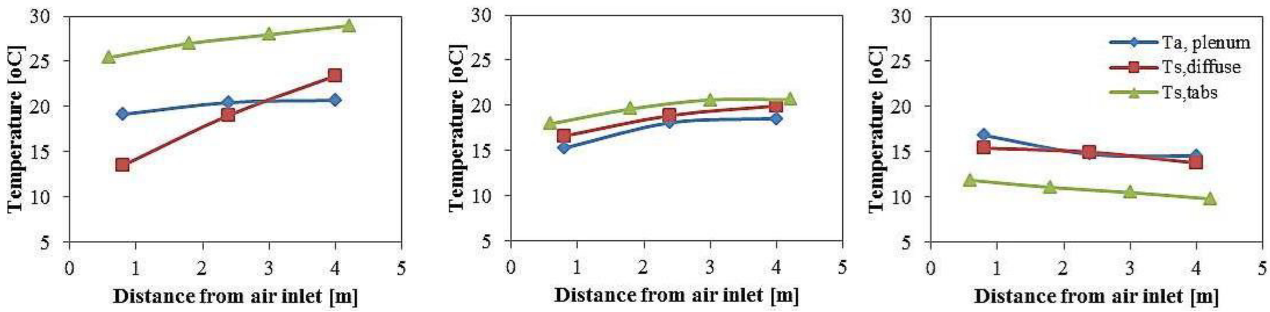


Fig.5. Pressure drop across single ceiling tile and across entire ceiling area



(a) (b) (c)

Fig. 6. Temperature distribution of plenum air, TABS lower surface and diffuse ceiling upper surface (a) Case 4 (b) Case 5 (c) Case 6

On the other hand, the thermal process in the plenum differs from ducted ventilation system because as the air passes through the plenum, it has directly contact with TABS and diffuse ceiling panel surface. Thus heat transfer will occur between plenum air, TABS and diffuse ceiling, depending on the temperature difference and flow rate. Figure 6 presents the air temperate distribution in the plenum and surface temperature distribution of the TABS and diffuse ceiling panels. First of all, the air temperature is not evenly distributed along the length of plenum. When TABS is operated in heating mode (Case 4), cool outdoor air is warmed up by the concrete slabs and diffuses ceiling panels, as it travels through the plenum. In the same manner, air is cooled down in Case 6 when TABS is activated in cooling mode. The variation in supply air temperature, also called as thermal decay [9], indicates that air is not perfectly mixed in the plenum and the air is not supplied with uniform temperature into the room. On the other hand, the plenum shows remarkable pre-heating or pre-cooling effect. Even the outdoor air temperature ranges from -6.87 ºC to 24.1 ºC, the air temperature in the plenum remains relatively stable (15 ºC-20 ºC). This significantly reduces the draught risk in the occupied zone by directly supplying cold outdoor air.

The TABS surface temperature distribution is exhibited to be non-uniform. The reason is that the water temperature decrease /increases along the pipe as it releases/ extracts heat to/from the room, so is the surface temperature. The heat transfer from TABS includes both radiation and convection. The radiation heat transfer is determined by surface temperatures and the view factor to the other surfaces. And the convection heat transfer is determined by the temperature difference between slab surface and the air as well as the convection heat transfer coefficient (related to air velocity), which is influenced by the air flow and water flow. In this study, the water flow in the pipe runs in opposite direction to air flow. The performance of TABS will be different if the water direction is changed and it can be discussed which direction gives a better thermal performance. The surface temperature of diffuse ceiling shows a similar trend as plenum air temperature. The big difference happens in the places closed to the inlet in Case 4. This is due to high density of cold air, instead of forming an air jet in a horizontal direction, the cold air drops on the diffuse ceiling and cools down the panels.

4. Conclusions

The objective of this study is to investigate the performance of an integrated system with diffuse ceiling ventilation and thermally activated building constructions. The experiments are conducted in climate chambers with an office layout and focus on thermal comfort in the occupied zone as well as thermal process and air flow pattern in the plenum. The experimental results indicate that a good thermal comfort level can reach by using diffuse ceiling, with no evidence of draught risk even in winter, low vertical temperature gradient and low radiant temperature asymmetry. The linear function between pressure drop across diffuse ceiling and air change rate points out that the air flow through diffuse ceiling is laminar. In addition, a pre-heating or pre-cooling effect is presented in the plenum. However, there is a thermal decay on the supply air, due to the heat exchange between air, TABS surface and diffuse ceiling panels. Finally, the thermal performance of TABS may influence by the water flow direction. A further study on the heat transfer between TABS and air by changing water direction needs to be conducted.

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